In re Patent Application of:
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IN THE DESCRIPTION

[1] This invention relates to an optical waveguide tap, which has substantially no polarization dependent loss from an input end to ~~and~~ an output tap end.

[3] The requirements to an optical tap are generally low insertion loss for the signal channel and minimal wavelength dependent loss (WDL) and polarization dependent loss (PDL) for the tapped channel.

[8] The operation of a directional coupler is based on coupled mode theory and is well described in the literature. Directional couplers have been disclosed by Derwyn C. Johnson and Kenneth O. Hill in United States Patents 4,291,940, 4,779,945, 4,900,119, 5,004,316, and 5,054,874 incorporated herein by reference. In essence, two waveguides are brought into close proximity for a predetermined length such that light from one of the waveguides couples to the adjacent waveguide. The amount of light which couples into the adjacent waveguide is determined by several factors including but not exclusive to the refractive index profiles of the waveguides, the separation of the waveguides and the length of the coupling region. The ~~lower~~ plot of Figure 1b shows the dependence of the coupling efficiency from waveguide 1 to waveguide 2 as a function of the coupling length for both polarization modes. The coupling is sinusoidal with the coupling length, with slightly different periods for the two polarizations Coupled mode theory determines that the coupling between waveguides will obey a sinusoidal dependence on directional coupler length as indicated in Figure 1b.

[10] For all-silica optical fiber based taps, the thermal expansion mismatch between the core and cladding material is low (typically <0.5ppm). Although fiber drawing is a high temperature process, the low coefficient of thermal expansion (CTE) mismatch means that thermal stresses generated in the materials are small with respect to planar silica-on-silicon devices and so stress induced birefringence is equally small in such optical fiber. In contrast, silica-on-silicon devices such as planar waveguides have very large CTE mismatches between core, cladding, and substrate materials resulting from the common necessity to deposit final overcladding layers with a much lower softening temperature than the already etched core layers. Thermal stresses are induced in the device during processing which lead to stress induced birefringence in the waveguiding region. The polarization dependence of directional coupler based taps is well known to be caused by stress induced birefringence leading to a difference in coupling lengths for the two polarizations (PDCR - polarization dependent coupling ratio). Coupling of TM modes is enhanced leading to a shorter coupling length for the TM polarization as ~~show~~ shown in Figure 1b, which schematically indicates the sinusoidal variation of power in the two waveguides as a function of the coupling region length. The difference in coupling strength means that the TE curve is stretched in the length axis with respect to the TM curve. Even though the tap is designed for very small coupling ratios, the real data shows that the PDL resulting from PDCR is still at an unacceptable level even for a tap ratio of -15dB.

[11] For silica-on-silicon devices one of the methods to achieve a polarization independent tap function is to compensate for the imbalance or higher coupling ratio of TM

mode in the tapped output of the directional coupler using additional waveguide devices with opposite optical characteristics, for example providing high loss for TM mode. Such a scheme is disclosed in United States Patent 5,539,850 in the names of Henry et al., where compensation was achieved using a second directional coupler that again preferentially couples the TM mode. This configuration is shown in Figure 2 where a first directional coupler 20 having an input trunk waveguide 22 is coupled to a first branch arm 24 which itself serves as a trunk arm from which a second compensating coupler 26 is disposed to couple into an unused branch 28. The tap waveguide 27 has an output that is compensated. Typically, this compensation is accomplished by choosing a short and a long coupling length such that the transmissions are on opposite~~s~~ sides of a sinusoidal peak as in Figure 1b, where the differences in transmission with polarization are <u>of</u> opposite ~~sign~~ <u>signs</u>.

[12] It is an object of this invention to provide a relatively inexpensive, controlled process and optical circuit substantially having no PDL in a optical tap between an input and output ~~port~~ <u>ports</u>, that would otherwise have suffered from significant PDL between its input and output ~~port~~ <u>ports</u>.

[13] In accordance with an aspect of this invention ~~there is provided~~, a planar optical waveguide tap substantially absent of polarization dependent loss from an input end to an output end <u>is provided</u>, comprising:

[36] Figure 9b illustrates <u>PDL</u> improvement from 0.35 dB (max) to less than 0.15 dB (max) across the 1520 nm to 1570nm wavelength band.

[37] Referring now to Figure 1, a waveguide circuit ~~a circuit~~ is shown which conveniently and inexpensively compensates for the polarization dependence of a tap for a silica-on-silicon waveguide device. An input port 102 is optically coupled by way of a directional coupler 100 to an output branch arm 104. The low PDL tap function is achieved through the use of a small ~~radii~~radius bend 106 on the tapped or branch arm. A same phenomenon that causes the TM polarization to more readily couple between waveguides in a directional coupler also causes a higher polarization dependent bend loss for small ~~radii~~ radius bends.

[39] Because TM modes couple more strongly to the tap or branch waveguide from a trunk waveguide, the tapped power level within the branch is slightly higher for the TM polarization than TE. This is illustrated in Figure [[3c]] 3a ~~at the bottom left~~ showing input-tap transmission. By adding a small ~~radii~~ radius bend to the tapped waveguide, an additional loss can be introduced which is higher for the TM polarization shown in Figure 3b, and thereby compensates for the PDL induced by the directional coupler. Of course it would be possible to optically couple a compensating waveguide having a predetermined bend therein to the output end of the tap waveguide instead of bending a portion of the tap waveguide itself. In general, changes to the material composition or waveguide dimension that influence the PDL of the directional coupler portion of the design similarly impacts the polarization dependence of the bend loss making the design robust to manufacturing variability. In the same manner that polarization dependence can be minimized through the bend compensation design, wavelength uniformity can also be

improved. Longer wavelengths couple more strongly in the directional coupler but are also radiated more quickly from the compensating bend. The result is a reduction in wavelength dependence of the bend compensated tap (BCT) with respect to standard single stage directional coupler based taps. By choosing the appropriate bend radius, both the PDL and wavelength tilt of the first directional coupler can be reduced as is shown in Figure [[5]] 3c.

[40] The key element in this invention is the use of a small ~~radii~~ radius bend curved waveguide inserted in a path downstream from the tap. The compensating bend design for typical tap ratios in the 1% to 10% range, uses a radius between 2 and 3 mm and a 90-degree total bend which may or may not occur in one continuous arc. Use of such a small ~~radii~~ radius bend in 0.7% to 0.8% delta waveguides is a novel design improvement. Standard design rules for 0.7% to 0.8% silica on silicon processes limit the minimum bend radius to >4.5 mm in order to avoid excessive optical loss. Although small radius bends do have high loss, for example, 2 dB, this is not crucial for a tap, as the directional coupler tap ratio can be adjusted to give the desired, overall tap ratio. Because of this high loss, waveguide designs using small bend radii downstream from a tap would only be used for PDL and wavelength dependence compensation of the tap. The simplicity, repeatability and reliability of this design compared to other compensating structures is highly advantageous.

[43] Small ~~radii~~ radius bend compensators also benefit arrays of integrated devices in an elegant way. Typical arrays of devices (such as VOAs) are arranged with their optical paths parallel to each other, and traveling from one edge of the

chip to the other. The device waveguides are spaced at a pitch determined be either the device characteristics (e.g. VOA thermal crosstalk) or the pitch of the mating fiber ribbon array at either edge on the chip. Often the waveguide pitch will vary across the chip. Tapped waveguides from devices in the center of the array must be brought to the chip edge, for fiber connection or to illuminate edge-mounted or flip-chip top-mounted mounted detectors. This can be done either by crossing neighboring guides, denoted crossing taps, or by remaining parallel to the array, called interdigitated taps.

[44] Small radius bend compensators benefit crossing taps by allowing a smaller device to device pitch. Low delta (0.7% to 8%) waveguides must cross at > 45 degrees to avoid high losses and crosstalk. To cross many guides, a crossing angle of 90 is often necessary to not induce excessive losses and the device waveguides. The small bend radius of 2 to 3 mm allows the first waveguide crossing to be at a larger angle for a given pitch as shown in Figure 8a. This enables higher levels of integration, which is a key path to cost reduction in integrated components. Crossing allows bringing the taps 80a through 80h from each waveguide to the edge of the chip where they can be separately coupled to fibers or detectors at locations 82a through 82h, the tap ~~waveguide~~ waveguides must cross the signal waveguides. The signal guides must be spaced far enough apart to allow the adjacent ~~tap~~ taps to cross at an angle great enough to prevent optical crosstalk or coupling. The use of small bend radius PDL compensators facilitates this because it allows closer spacing of the signal guides for the same crossing angle restriction.